Influence of asymmetrical topology on service performance of railway prestressed concrete sleepers

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Abstract

Railway networks are the catalyst for economic and societal growth of the cities, region and country. Their physical assets consist of infrastructure, rolling stock, signaling systems and electrification. By nature, the railway infrastructure is nonlinear, judging from its behaviors, geometry and alignment, wheel-rail contact condition and operational parameters such as tractive efforts. It is noted that degradation of ballast over time has not been considered in most train-track interaction models. Indeed, the ballast degradation can cause differential settlement along the track and induce dynamic impact forces acting on partial and unsupported tracks. In addition, it is reportedly that ballast damages underneath a local railseat can cause the risk of centre-bound cracks in concrete sleepers due to the unbalanced support under sleepers. These cracks are initially vertical under bending mode and can be further developed, resulting in unsecured spreading rail gauge. This paper presents nonlinear finite element simulations of concrete sleepers in a track system. The simulations take into account the tensionless nature of ballast support coupled with the asymmetric topology. The finite element model was calibrated using static and dynamic responses in the past. In this paper, the influences of topologic asymmetry on both static and dynamic behaviors of sleepers are firstly highlighted. The topology asymmetry is often caused by on-site modification for structural retrofit or local track timber-plating component arrangements. In

addition, it is the first to demonstrate the effects of sleeper length on the service performance of concrete sleepers at risk. The insight into the influences of asymmetric topology will help improve the rail construction criteria in order to adjust support profile and appropriately mitigate sleeper/ballast interaction.

Keywords: Railway sleepers, crosstie, asymmetric support, performance based design, vulnerability.

1. Introduction

It is commonly known that railway sleepers (also called 'railroad tie' in North America) are essential elements of railway track structures. Two of their major duties are: first, to distribute train wheel loads from the rails to the underlying track bed and foundation; second, to maintain and secure track gauge for safe and smooth train passages. Based on present design practices, the design life span of the concrete sleepers is targeted at around 50 years in Australia, Asia and North America [1-4]; and around 70 years in Europe [5]. Note that the exact design principle in Europe has not been fully addressed due to the recent development of Eurocode. Figure 1 shows the typical ballasted railway tracks and their key components. There have been a number of recent investigations on the railway sleeper models [6-9]. For fast computations, most of the models in practice adopted the concept of beam on elastic foundation where a sleeper is laid on the elastic support, acting like a series of springs. It is reported that only vertical stiffness is sufficient to simulate the ballast support condition because the lateral stiffness seems to play an insignificant role in sleeper's bending responses and overall structural strength [10-11].

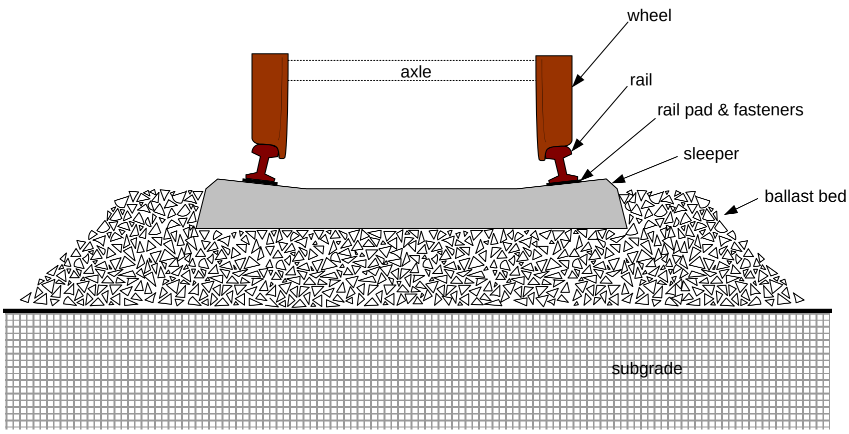


Fig. 1. Typical ballasted railway track components.

In fact, many field measurements suggest a diverse range of sleeper flexural behaviors, which are largely dependent to the support condition induced by ballast packing and tamping, as well as to track components such as rail pads and fastening systems [12-18]. However, it is found that the static and dynamic behaviors of railway sleepers with asymmetrical topology (dimensional changes) have not been fully investigated [19]. Figure 2 shows a typical layout of a track turnout system, where asymmetrical topology can often be observed [20]. A railway turnout system have generally been analysed the using a grillage beam method [21]. It is however noted that similar type of sleepers with the dimensional changes can also be caused by on-site modification during construction and maintenance of railway tracks.

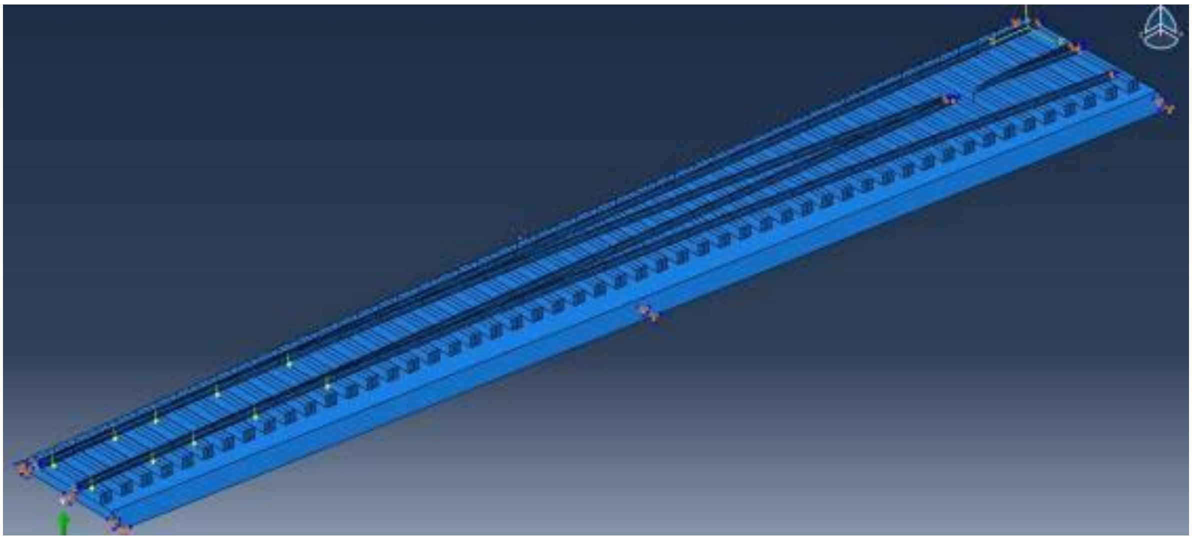


Fig. 2. Typical turnout system layout, adopted from [20].

It is apparent that there are a number of railway sleepers that are topologically asymmetrical. However, research and investigation into their reduced service performance has not been adequately carried out. This paper presents an advanced railway concrete sleeper modeling capable of static and dynamic analysis into the nonlinear effect of topological asymmetry on the flexural responses and service performance of railway sleepers. In this paper, the focus is placed on the flexural response and eigen behavior of the railway concrete sleepers subjected to various spectra of ballast stiffness at the mid span, in comparison with the current design method in accordance with the design standards. The insight obtained will help track and rail engineers to enhance predictive track maintenance regime and condition monitoring strategy that could improve reliability, availability, maintainability and safety (RAMS) of a railway network.

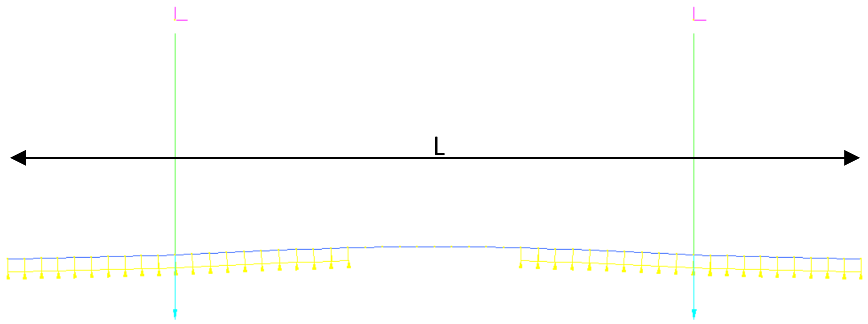
2. Materials and finite element method

2.1 Finite element simulations

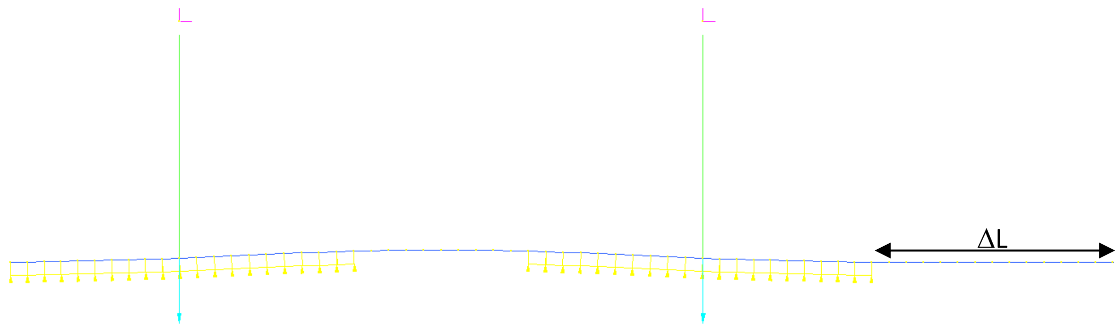
Extensive researches since 1990s have revealed that the two-dimensional Timoshenko beam model is the most suitable option for modeling concrete sleepers under vertical loads [6-8]. In this simulation, the finite element model of concrete sleeper (optimal length) has been adopted from the previous development that has been calibrated against the numerical and experimental modal parameters [11-15]. Figure 3 shows the extended version of the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 (G+D Computing, 2001), the numerical model included the beam elements, which take into account shear and flexural deformations, for modeling the concrete sleeper. The trapezoidal cross-section was assigned to the sleeper elements. The rails and rail pads at railseats were simulated using a series of spring. In this study, the sleeper behaviour is stressed so that very small stiffness values were assigned to these springs. In reality, the ballast support is made of loose, coarse, granular materials with high internal friction. It is often a mix of crushed stone, gravel, and crushed gravel through a specific particle size distribution. It should be noted that the ballast provides resistance to compression only.

As a result, the use of elastic foundation in the current standards in Australia and North America [1, 22, 23] does not well represent the real uplift behaviour of sleepers in hogging moment region (or mid span zone of railway sleeper). In this study, the support condition was simulated using the tensionless beam support feature in Strand7 [24]. This attribute allows the beam to lift or hover over the support while the tensile supporting stiffness is omitted. The tensionless support option can correctly represent the ballast characteristics in real tracks [24]. Table 1 shows the geometrical and material properties of the finite element model. It is important to note that the parameters in Table 1 give a representation of a specific rail track. These data have been validated and the verification results have been presented elsewhere [25-26].

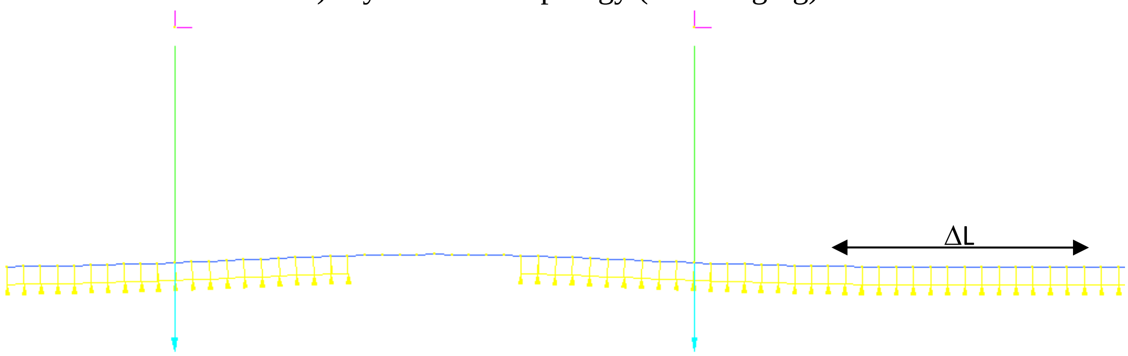
Based on our critical literature review, the flexural influences on railway concrete sleepers due to the variations of ballast support conditions together with the asymmetric topology of sleeper has not yet addressed by the past researchers [21, 23, 27]. Especially when the uplift behaviour due to ballast tensionless support in hogging region of sleepers is considered, a finite element analysis is thus required to supersede the simple manual calculation. For this study, the numerical simulations have been extended to conduct the performance analyses using the nonlinear solver in STRAND7. The effects of asymmetric topology of concrete sleepers on their flexural responses in a railway track system can be evaluated. The length of sleepers varies from 2.5m to 4.0m, which is practically common in the 2 and 3 rail-seats sections (see Figure 3).



a) symmetrical topology



b) asymmetrical topology (overhanging)



c) asymmetrical topology (fully supported)

Figure 3 STRAND7 finite element models of railway sleepers with asymmetrical topology

Table1 Engineering properties of the standard sleeper used in the model

Definition	Parameter	Unit
Flexural rigidity	$EI_c = 4.60,\ EI_r = 6.41$	MN/m^2
Shear rigidity	$\kappa GA_c = 502,\ \kappa GA_r = 628$	MN
Ballast stiffness	$k_b = 13$	MN/m^2
Rail pad stiffness	$k_p = 17$	MN/m
Sleeper density	$\rho_s = 2{,}750$	kg/m^3
Sleeper length	$L = 2.5$	m
Rail track width	$g_t = 1.5$	m

3. Flexural responses

Using the design data in Table 1, the static bending moment envelops along the sleeper when subjected to the equal wheel loads of 100kN at both railseats in comparison with the standard design moments can be shown in Figures 4 and 5. Based on AS1085.14 (Standards Australia, 2003), the design maximum positive bending moment at the rail seat = 12.50 kNm, while the centre negative design bending moment = 6.95 kNm (if considered half support) or =12.50 kNm (if considered full support). It is typical that the positive and negative moments are associated with the railseat and mid-span sections, respectively. It shows that the standard design moments provide the conservative results. The standard design moment at mid span is about half between the other two cases (see Figure 3).

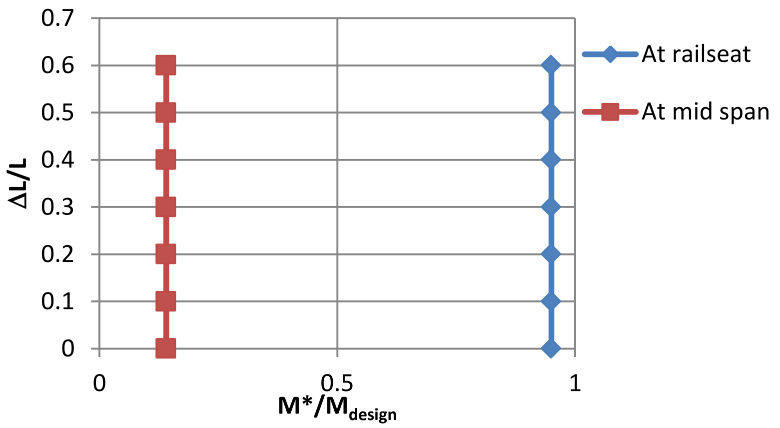


Figure 4 Maximum bending moment of overhanging sleeper

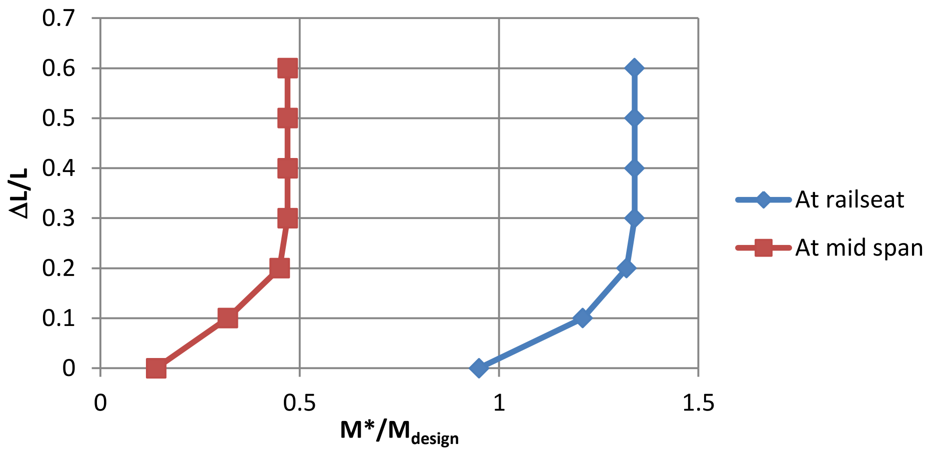


Figure 5 Maximum bending moment of fully-supported sleeper

Figures 4 and 5 exhibit clearly that the influence of the asymmetrical topology is pronounced when a contact between bearer and ballast layer exists. Considering field investigation, such the contact could occur when there is a differential settlement on the mainline track (for example, run-through turnout road). Once the ballast-bearer contact establishes, the bearer will take additional bending moment at the inner railseat.

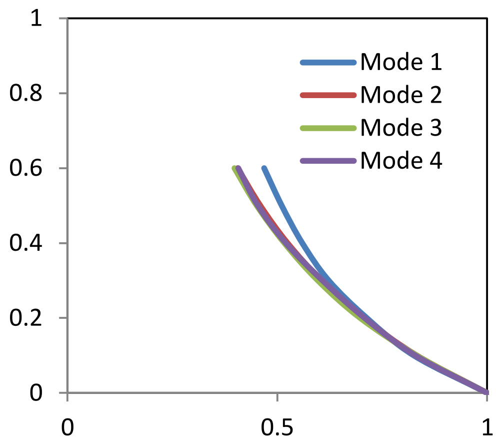


Figure 6 Dynamic behaviour of overhanging sleeper

4. Natural Frequencies

The natural frequencies of the railway sleepers with asymmetrical topology can be observed in Figures 6 and 7. It can be seen that the topology of bearer plays a key role in dynamic natural frequencies and corresponding mode shapes of the bearers. Overhanging bearers tend to be relatively much affected by the topology aspect in comparison with the dynamic behavior of fully supported bearers. Figures 6 and 7 clearly display the dynamic softening behavior of the railway sleepers with asymmetrical topology. It is clear that the dynamic softening is more pronounced at a higher frequency range.

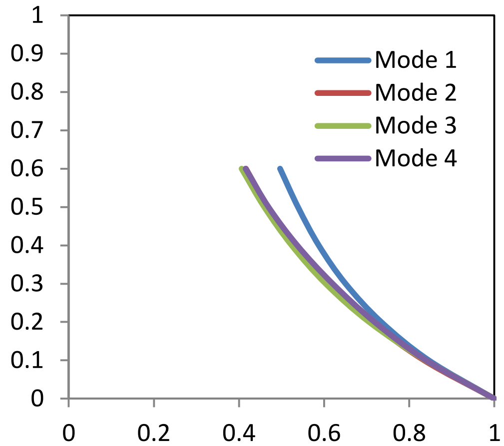


Figure 7 Dynamic behaviour of fully-supported sleeper

5. Conclusions

Railway sleepers with asymmetric topology are very common in practice, evidenced by on-site modification of railway sleepers. This paper presents numerical simulations of the railway sleepers with asymmetric topology in order to investigate nonlinear mechanics and dynamics induced by the critical structural effects of a variety of ballast conditions and asymmetric topology. The flexural responses and free vibration behaviors of the railway sleepers and bearers in a turnout system (switches and crossings) have been highlighted. The finite element model of railway sleepers, which was established and calibrated earlier, has been extended for investigations in this study. The influences of the variation of ballast support conditions at sleeper end together with the asymmetric length of sleepers on the bending of the railway sleeper are highlighted in comparison with the standard design. By using the nonlinear solver in STRAND7, nonlinear sleeper/ballast contact mechanics can be simulated. Under static and free vibration conditions for overhanging and supported bearers, the numerical results exhibit that the bending moment resultants are barely affected by topological aspects when the ballast-sleeper contact is not established. The standard design bending moments tend to be overestimated for the overhanging sleeper, whilst they can be highly underestimated when sleeper end is laid on ballast. Generally, positive bending moments at inner railseat of sleeper have generally high sensitivity to the spectrum of ballast support conditions in comparison with the more pronounced influence of sleeper length. In such case, the nominal bending moment at inner railseat could be larger than the structural capacity of sleeper and resulted in structural cracks and failure. In contrast, such behavior is insignificant and tolerable for overhanging sleepers. In addition, it is found that the asymmetrical topology induces dynamic softening in the railway sleepers with asymmetrical topology. This implies that the asymmetrical sleepers are prone to damage under high-intensity impact loading.

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